The interaction between the projectile and the target core in single ionization of helium by 100 MeV/u C^{6+} and 1 GeV/u U^{92+} ions

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Abstract

We consider single ionization of helium by fast highly charged ions. The ionization is treated as a three-body problem which involves the 'active' target electron, the target core (consisting of the target nucleus and the 'passive' target electron) and the projectile-ion. We show that, unless the transverse momentum transfer in the collision is large, the deviation of the interaction between the projectile and the target core from the purely coulomb law has a weak effect on the ionization. In particular, the account of this deviation does not enable one to get an agreement with experimental data on the fully differential cross section for the electron emission into the so called perpendicular plane.

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1 Introduction

Collisions of fast highly charged ions with helium represent an interesting example of quantum dynamical few-body systems [1]. During the last several years single ionization of helium has attracted a lot of attention, both experimental and theoretical [2]- [10].

The most detailed information on the process of ionization is obtained by exploring the collision dynamics on the level of the fully differential cross section (FDCS). The parameter $\eta_p = Z_p/v_p$, where Z_p is the projectile charge and v_p the collision velocity, is commonly used to characterize the effective strength of the projectile-target interaction. At small values of η_p ($\eta_p \ll 1$), where the projectile-target interaction is weak, one normally expects that already the first-order Born approximation should yield a reasonable description of the collisions.

However, such expectations have been put into question by experimental results on single ionization of helium by 100 MeV/u C^{6+} projectiles. At this impact energy the collision velocity is quite high ($v_p = 58$ a.u.) leading to the collision strength parameter η_p of just about 0.1. Nevertheless, large discrepancies were found between the experimental data and the first Born results for the electron emission outside the scattering plane [1]. At the same time, for the electrons

[1] The scattering plane is a plane spanned by the vectors of the initial and final projectile momenta.

emitted into the scattering plane the experimental FDCS was reasonably well reproduced by first Born theory [2].

It was suggested in [3] that the discrepancies might have their origin in the interaction between the projectile and the target core (the target nucleus and the passive atomic electron). According to the first Born approximation, this interaction does not influence the ionization transition amplitude. Therefore, a number of theoretical models including, in particular, the second Born, the Glauber, the continuum-distorted-wave-eikonal-initial-state (CDW-EIS) and the symmetric-eikonal approximations were applied to study the electron emission. All these models go beyond the first Born approximation and, in particular, include the interaction between the projectile and the target core.

These models predicted noticeable deviations in the electron emission pattern from the first Born results, especially outside the scattering plane [11]. It also should be noted that in the case of the ionization by 100 MeV/u C^{6+} ions the predictions of these models concerning the character of the deviations and their magnitude were quite similar [11]. In particular, according to all of these models the main reason for the deviations in the FDCS from the first Born results in this case is the interaction between the projectile and the target core.

These models, however, did not enable one to get any better overall agreement with the experiment [3]. Moreover, for the FDCS for the electrons emitted into the plane, perpendicular to the transverse momentum transfer (the perpendicular plane), they all predicted a minimum exactly there where, according to the experiment, a maximum should be. Since for this plane the first Born approximation predicts almost a constant value for the emission pattern (see also figure 3) [2], the disagreement between the experiment and theory actually had became even worse.

It was then suggested [9] that the difference between the experiment and theory is not a signature of any principal shortcoming of the atomic collision models but is simply caused by the thermal motion of the target atoms. Because of this motion a detection of the final momentum of the recoil ion does not allow one to get precise information about the value and direction of the momentum transfer in the collision. As a result, the orientation of the perpendicular plane becomes experimentally not very well defined and the measured emission into this plane can contain noticeable admixtures of the emission into other planes, including 'traces' of the (relatively very large) binary peak from the scattering plane.

The role of possible experimental uncertainties was later studied in [10]. It was confirmed that a non-zero temperature of the target gas indeed results in the appearance of a maximum in the emission spectra exactly there where it was observed in the experiment. Besides, the authors of [10] found out that the size of the projectile beam also contributes to the appearance of the maximum. Nevertheless, the above two effects seem to be insufficient in order to fully explain the difference between the experiment data and theoretical results.

In another recent paper [12] it was suggested that the reason for the discrepancies could lie in the fact that in the theoretical models, used so far to describe this process, the interaction between the projectile and the target core was taken as a pure coulomb interaction between two point-like charges: Z_p and 1 for the projectile and target core, respectively. Strictly speaking

[2] According to the first Born approximation the electron emission pattern should be a constant in the plane, which is perpendicular to the vector of the total momentum transfer. However, under the conditions of the experiment [3], because of high collision velocity, the minimum momentum transfer was very small and the transverse part of the momentum transfer practically coincided with the total momentum transfer.

such an approximation is only valid for collisions with impact parameters larger than the size of a helium atom. If a substantial part of the electron emission arises in collisions, in which the projectile penetrates the target core, the above theoretical models might be not able to yield a satisfactory description of the ionization process. A similar suggestion has been also made in [13].

It is, therefore, one of the main intentions of the present paper to attempt to find out whether the account of a non-coulomb part of the interaction between the projectile and target core could bring substantial changes into the form of calculated cross sections and, in particular, whether this account can improve the description of the experimental data on single ionization of helium by 100 MeV/u C^{6+} projectiles. Besides, for a comparison we shall also consider single ionization of helium by 1 GeV/u U^{92+} ions. In the latter case the collision velocity is even by a factor of 2 higher ($v_p = 120$ a.u.) but the parameter $\eta_p = Z_p/v_p$ is rather close to 1 ($\eta_p = 0.77$).

Atomic units are used throughout except where otherwise stated.

2 Theoretical model

We shall treat single ionization of helium by considering a three-body model of this process. This model involves the active target electron (1), the target core (2) and the projectile (3). The projectile and the active electron interact via the (relativistic) Coulomb force. The target core consisting of the target nucleus and the passive electron is supposed to behave in the collision as a rigid body whose internal structure is not changed by the collision.

It is well known that even in collisions at relativistic impact velocities the majority of electrons emitted from such a light target like helium has velocities with respect to the target recoil ion which do not exceed a few atomic units. Therefore, we shall consider the ionization using the rest frame of the target nucleus and describe the active electron nonrelativistically.

In this frame the field of the target core acting on the active electron and the projectile is described by a scalar potential. This potential is taken to be the same for the active electron and the projectile (as well as for the initial and final collision channels) and is approximated by

$$\Phi(\xi) = \frac{1}{\xi} + (1 + \beta\xi)\,\frac{\exp(-\alpha\xi)}{\xi}. \tag{1}$$

Here ξ refers to the distance measured from the center of the target core (i.e. from the target nucleus) and is given in the target frame. In accordance with results of [14] the values of the parameters α and β were chosen to be 3.36 a.u. and 1.665 a.u., respectively.

The initial state of the colliding system is taken as a product of unperturbed states of the projectile and target electron multiplied by the eikonal factors. These factors reflect the distortion of the initial state caused by the coulomb interaction between the projectile and the active electron and by the interaction between the projectile and the target core. The final state is represented by a similar product where, however, the eikonal distortion factor for the projectile-active electron subsystem is replaced by a (relativistic) continuum-distorted-wave factor. The initial and final unperturbed states of the electron moving in the field of the target core are obtained by a numerical solution of the corresponding Schrödinger equation.

The main difference between the approach of the present paper and our previous attempt [7]-[8] to address the problem of helium single ionization by very fast ions is that the interaction

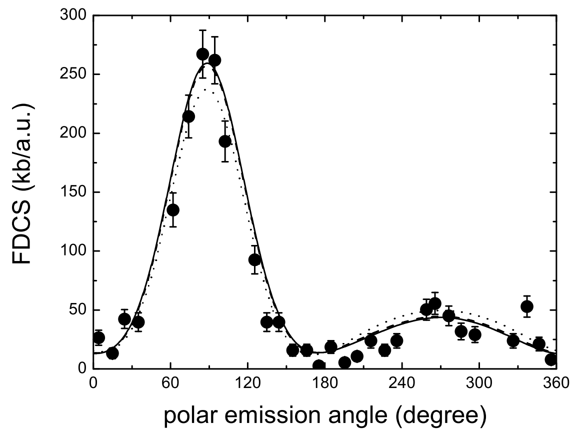

Figure 1: The FDCS for single ionization of helium by 100 MeV/u C^{6+} projectiles plotted as a function of the polar emission angle. The cross section is given in the scattering plane. The electron emission energy $\varepsilon_k = 6.5$ eV and the total momentum transfer $q = 0.65$ a.u.. Symbols: experimental data from [2]. Solid curve: results obtained by including into the interaction between the projectile and the target core the full expression (1). Dash curve: the projectile-target core interaction is modeled by the coulomb part of (1) only. Dot curve: the first Born results.

between the projectile and the target core, in addition to the coulomb part, involves also the short-range interaction (see Eq.(1)). Besides, an eikonal-like description of the projectile-active electron coupling in the final channel has now been replaced by the continuum-wave coulomb distortion factor. The latter is taken in such a way as to account for the necessary relativistic changes appearing in the form of the coulomb field generated by a very fast moving ion.

The first-order counterpart of the present three-body model is obtained if all the distortion factors are set to unity. In particular, within the first order approach the interaction between the projectile and the target core completely drops out from the transition amplitude. Besides, the interaction between the projectile and the active target electron is reduced just to a single-photon exchange.

3 Results and discussion

3.1 The fully differential cross section

Let us now turn to considering the FDCS for single ionization of helium, $\frac{d\sigma^+}{d^2\mathbf{Q}d^3\mathbf{k}}$. Here, $\mathbf{Q}$ is the transverse part of the total momentum transfer to the target which given by $\mathbf{q} = (\mathbf{Q}, q_{min})$, where $q_{min} = (\varepsilon_k - \varepsilon_0)/v_p$ with ε_0 and ε_k being the initial and final energies of the active electron. $\mathbf{k}$ is the momentum of the emitted electron with respect to the target nucleus. We shall first consider the ionization caused by 100 MeV/u C^{6+} projectiles.

In figures 1-2 we show the FDCS for the scattering plane. This plane is defined by the condition $\varphi_k = 0^0$, where the azimuthal angle φ_k of the momentum $\mathbf{k}$ of the emitted electron is

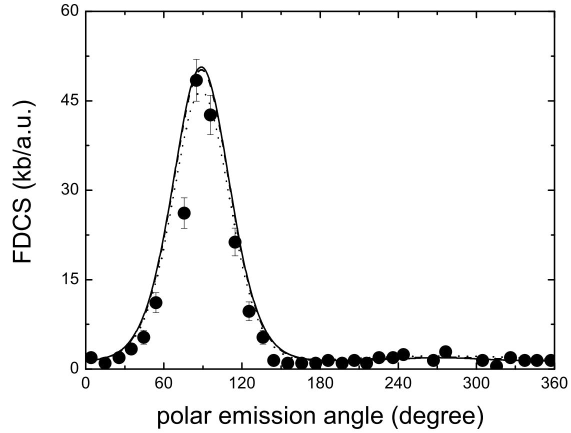

Figure 2: Same as in figure 1 but for the electron emission energy of 17.5 eV and the total momentum transfer of 1.43 a.u..

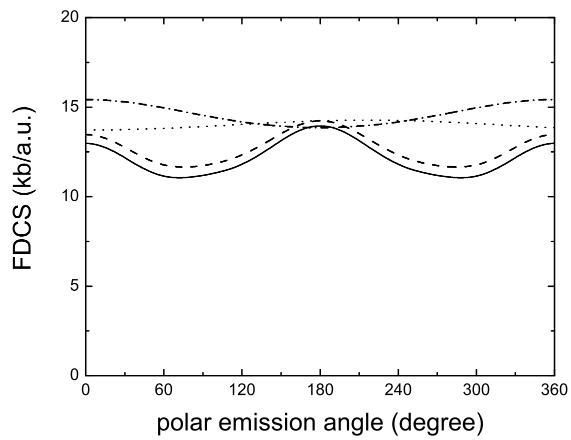

Figure 3: Same as in figure 1 but the cross section is given in the perpendicular plane. Besides, the dash-dot curve displays results of the calculation in which the interaction between the projectile and the active electron is described within the rCDW-EIS but the projectile-target core interaction is ignored.

counted from the direction of the transverse momentum transfer $\mathbf{Q}$. This cross section is given as a function of the polar angle, $\vartheta_{\mathbf{k}} = \arccos(\mathbf{k} \cdot \mathbf{v}_p / k v_p)$, of the momentum of the emitted electron for fixed emission energy and momentum transfer. The results are on an absolute scale.

We observe in these figures familiar structures: at the lower momentum transfer (see figure 1) the emission pattern clearly exhibits the so called binary and recoil peaks; at the higher momentum (see figure 2) the recoil peak practically disappears. It is also seen in these figures

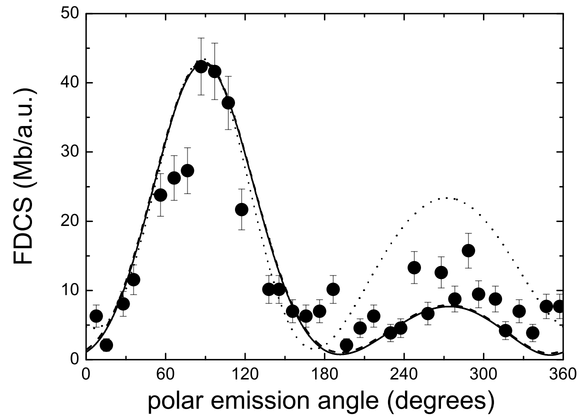

Figure 4: The FDCS for single ionization of helium by 1 GeV/u U^{92+} projectiles plotted as a function of the polar emission angle. The cross section is given in the scattering plane. The electron emission energy $\varepsilon_k = 2$ eV and the total momentum transfer $q = 0.65$ a.u.. Symbols: experimental data from [7], these data have been fit to the maximum of the solid curve. Solid curve: results obtained by including into the interaction between the projectile and the target core the full expression (1). Dash curve: the projectile-target core interaction is modeled by the coulomb part of (1) only. Dot curve: the first Born results.

that, while the inclusion of the interaction between the projectile and the target core has a visible (although rather weak) impact on the calculated cross section, the latter is practically insensitive to whether this interaction is approximated by merely the coulomb part of the scalar potential (1) or by the full expression (1).

The situation becomes somewhat different if we consider the emission into the perpendicular plane (see figure 3). The latter is defined by the condition $\varphi_k = 90^0$. The emission into this plane is very weak and much more sensitive to the details of a theoretical description. For this plane the deviations between the results calculated in the different approximations become more pronounced. In this plane the higher order contributions in the interaction between the projectile and the active electron change the shape of the cross section. The inclusion of the interaction between the projectile and the target core brings further quite noticeable changes into the calculated emission pattern. Moreover, in the perpendicular plane we also observe that there is a visible effect in the emission spectrum caused by the short-range part of this interaction.

However, in contrast to the experimental data showing a pronounced maximum at $\vartheta_k \sim 90^0$ and 270^0 (see e.g. [10]), the inclusion of the interaction between the projectile and the target core results in a minimum in the calculated emission spectrum. Moreover, this minimum becomes even slightly deeper if the short range part of this interaction in taken into account. Thus, the present model is unable to explain the appearance of the maximum at $\vartheta_k \simeq 90^0$ observed in the experimental data.

Let us now turn to the FDCS in collisions with 1 GeV/u U^{92+} projectiles. In figures 4-5 we plot the FDCS for the scattering plane as a function of the polar angle of the emitted electron. Theoretical results shown in these figures are on an absolute scale. The experimental data are

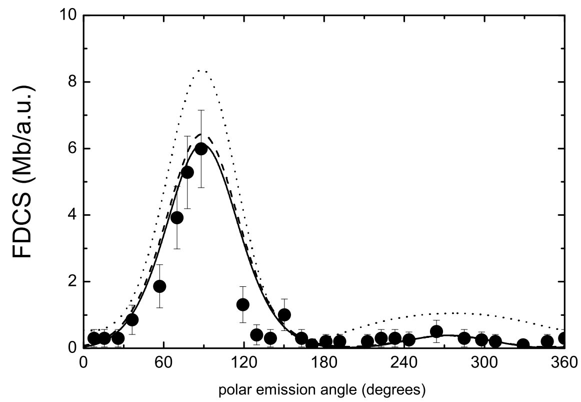

Figure 5: Same as in figure 4 but for the electron emission energy of 10 eV and the total momentum transfer of 1 a.u..

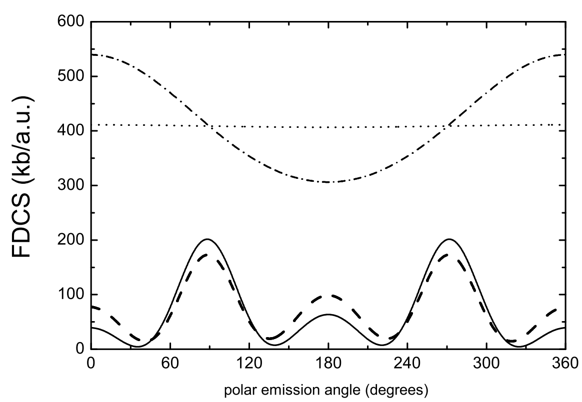

Figure 6: Same as in figure 5 but the cross section is given in the perpendicular plane. Besides, the dash-dot curve displays results of the calculation in which the interaction between the projectile and the active electron is described within the rCDW-EIS but the projectile-target core interaction is ignored.

normalized (at the cross section maximum) to those theoretical results which are obtained with the inclusion of the full interaction between the projectile and the target core.

Like in the previous case, the main feature of the emission pattern is the presence of the binary and recoil peaks. However, in contrast to the case of helium ionization by 100 MeV/u C^{6+} ions, the calculated cross section in collisions with the 1 GeV/u uranium ions substantially depends on whether or not the interaction between the projectile and the target core is taken into account. The effect of the short-range part of this interaction also becomes somewhat more visible. Nevertheless, for the collision parameters considered in figures 4 and 5 the calculated spectrum of the electron emission into the scattering plane still changes very little when the

short-range part of the potential (1) is taken into account.

Results for the electron emission into the perpendicular plane are shown in figure 6. Like in the case with the carbon projectiles, the calculated FDCS for the emission into this plane turns out to be much more sensitive to the approximations used. In particular, the inclusion of the interaction between the projectile and the target core substantially reduces the magnitude of the calculated cross section and has a very strong impact on its shape. Besides, the inclusion of the short range part of the potential (1) into this interaction results in a more pronounced effect. One more interesting feature of the emission pattern shown in figure 6 is that the maximum in the emission is situated now at $\simeq 90^0$ and not at 0^0 (or 180^0) as it was in the case with the carbon projectiles. This finding is in agreement with our earlier predictions [11], [15] that, when the effective strength of the projectile field increases, a minimum in the calculated cross section at $\simeq 90^0$ disappears and, instead, the cross section attains a maximum at this point.

3.2 Cross section differential in the emission energy and transverse momentum transfer

The influence of the interaction between the projectile and the target core on the dynamics of single ionization of helium in general depends not only on the electron emission energy, the momentum transfer and the magnitude of the parameter η_p but also on a plane chosen to observe the FDCS. In order to get some more 'integral' ideas about the influence of the projectile-target core interaction as well as of the importance of its coulomb and short-range parts on the collision process we shall now consider the ionization cross section differential in the emission energy and the transverse part of the momentum transfer, $d^2\sigma^{(+)}/dQd\varepsilon_k$. Such a cross section is shown in figures 7 and 8 where it is considered as a function of the transverse momentum Q at fixed values of the emission energy ε_k.

In the case of single ionization of helium by 100 MeV/u C^{6+} projectiles noticeable differences in the cross section calculated without and with including the interaction between the projectile and the target core begin starting with $Q \simeq$ 3-4 a.u. (see figure 7). In this figure we also see that at about the same values of Q the short-range part of this interaction begins to have a visible effect on the cross section. This effect increases with increasing Q and changes the cross section by about a factor of 2 at $Q \simeq 5$ a.u..

Compared to collisions with the carbon ions, the dynamics of single ionization of helium by 1 GeV/u U^{92+} projectiles is much stronger affected by the interaction between the projectile and the target core which is clearly seen in figure 8. Now the differences in the calculated cross sections caused by this interaction start already at $Q \simeq 0.5$ a.u.. Besides, the effect of the short range part of this interaction becomes noticeable at $Q \simeq$ 2-3 a.u. and, thus, also comes into play at comparatively smaller values of Q.

4 Conclusions

We have considered some aspects of single ionization of helium by very fast highly charged nuclei. In this consideration we concentrated on the effects on the dynamics of this process caused by the interaction between the projectile-nuclei and the helium core and were especially interested in the role played by the short-range part of this interaction. As one could expect

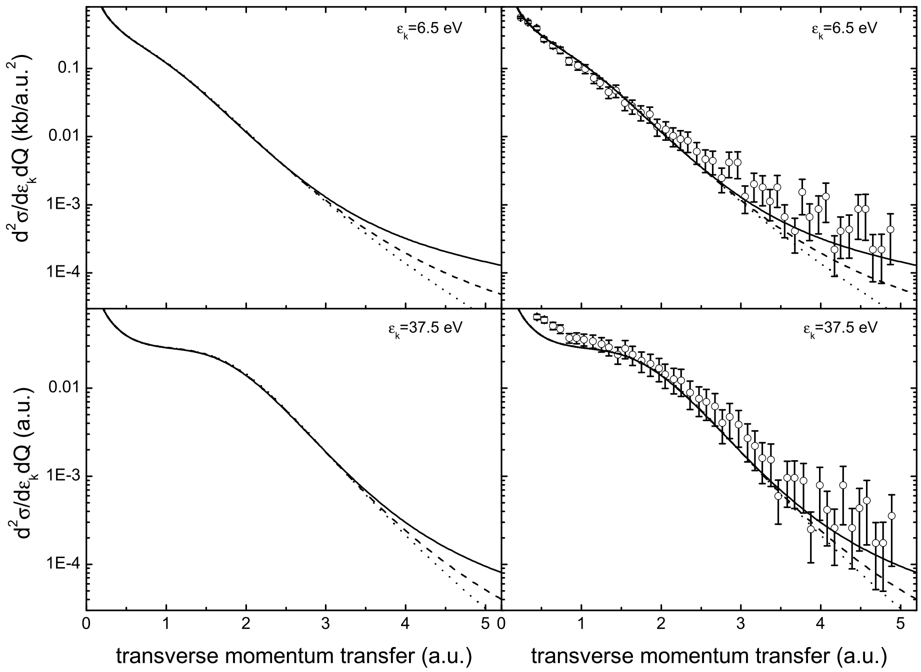

Figure 7: The doubly differential cross section $d^2\sigma/d\varepsilon_k dQ$ for single ionization of helium by 100 MeV/u C^{6+} projectiles given as a function of the transverse momentum transfer Q at a fixed value of the emission energy (ε_k = 6.5 and ε_k = 37.5 eV for the upper and lower panels, respectively, of the figure). The left panels of the figure: solid curves are results obtained by including into the interaction between the projectile and the target core the full expression (1); dash curves shows the results obtained when the projectile-target core interaction is modeled by the coulomb part of (1) only; dot curves are the first Born results. The right panels: the same as in the left panels plus experimental data from [2].

the role of this interaction as well as that of its short range part were found to increase when the transverse momentum transfer increases. It was also shown that they may result in very substantial effects. In particular, the inclusion of this interaction in the form (1) enables one to get a better description of the experimental data of [2] on the doubly differential ionization cross section at larger values of Q.

However, at smaller values of Q, for which the experimental data on the fully differential cross sections are available, our consideration shows that the short-range part of this interaction, both in collisions with 100 MeV/u C^{6+} and 1 GeV/u U^{92+} projectiles, has a very weak influence on the form and absolute values of the fully and doubly differential cross sections. Thus, our present study does not support the idea expressed in [12] and [13] that the neglect of the short-range part of this interaction in the previous theoretical models could be responsible for the very substantial deviations between the experiment and theory in the case of the electron emission into the perpendicular plane.

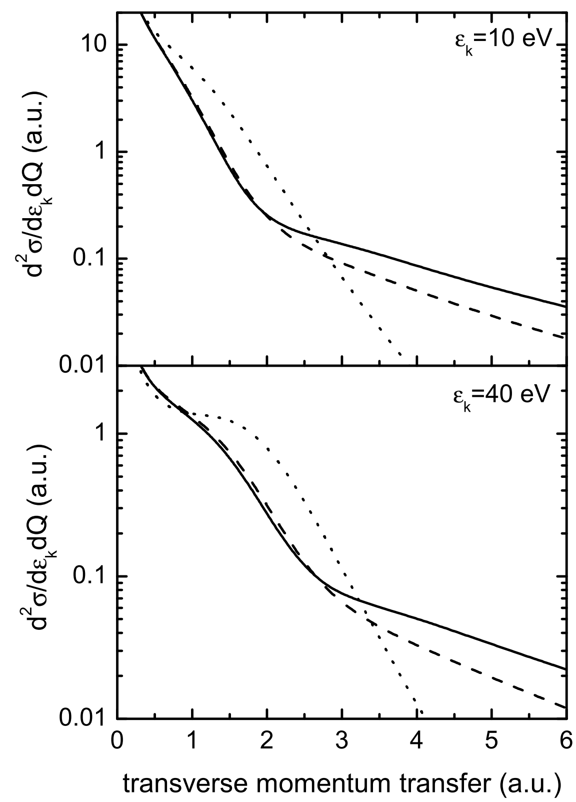

Figure 8: The doubly differential cross section $d^2\sigma/d\varepsilon_k dQ$ for single ionization of helium by 1 GeV/u U^{92+} projectiles given as a function of the transverse momentum transfer Q at a fixed value of the emission energy ($\varepsilon_k = 10$ and $\varepsilon_k = 40$ eV for the upper and lower panels, respectively, of the figure). Solid curve: results obtained by including into the interaction between the projectile and the target core the full expression (1). Dash curve: the projectile-target core interaction is modeled by the coulomb part of (1) only. Dot curve: the first Born results.

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